Neutrino fluxes from CNO cycle in the Sun in the non stationary case with mixing.

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Abstract. The computational analyses is presented of the non stationary case with mixing of the solar model when the neutrino flux F_{13} from the decay of ^{13}N is higher than a standard solar model predicts.

neutrino experiments, solar abundance, solar interior

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1. Introduction

Recently it has been argued [1]– [3] that to achieve agreement of the solar surface heavy element abundance with the results of helioseismology [4, 5] probably one needs to introduce some non stationary process in the solar model. In the paper [6] we addressed the question how the mixing in the Sun can change the fluxes of neutrinos generated in the CNO cycle. The point which drew our attention was that there is a large difference of abundance of carbon in the central and peripheral layers due to burning of carbon in thermonuclear reactions in the center of the Sun. This makes possible to obtain a relatively large increase of the flux F_{13} from the decay of ^{13}N even for a very mild mixing between the central and peripheral layers of the Sun while all other neutrino fluxes and other observable are not practically changed. Looking for the effect of mixing we have omitted coordinates in our consideration neglecting the specific character of the mixing, paying attention only on the evolutionary part of equations.

$$\begin{cases} dX(^{12}C)/dt = -\lambda(^{12}C)X(^{12}C) + \frac{12}{15}\lambda(^{15}N)X(^{15}N)+ \\ \qquad +k(X_0(^{12}C) - X(^{12}C)) \\ dX(^{13}C)/dt = -\lambda(^{13}C)X(^{13}C) + \frac{13}{12}\lambda(^{12}C)X(^{12}C) - kX(^{13}C) \\ dX(^{14}N)/dt = -\lambda(^{14}N)X(^{14}N) + \frac{14}{13}\lambda(^{13}C)X(^{13}C)+ \\ \qquad +k(X_0(^{14}N) - X(^{14}N)) \\ dX(^{15}N)/dt = -\lambda(^{15}N)X(^{15}N) + \frac{15}{14}\lambda(^{14}N)X(^{14}N) - kX(^{15}N) \end{cases} \qquad (1)$$

where $X(^AZ)$ and $X_0(^AZ)$ – the abundance of isotope ^AZ in the central and peripheral regions, $\lambda(^AZ) = \rho N_A X(^1H) <^A Zp>$ – the $(p +^A Z)$ reaction nuclear rate [7, 8], k – the mass transport coefficient. Here the mixing is understood as a spherically asymmetric process when the masses coming to the core of the Sun and leaving the core go by different paths. So this differs from gravitational settling and diffusion and in this sense is a 3D extension of the standard solar model which is known to be a 1D model. But we followed a simplified approach. We used a weak mixing (which means that it involves very weak mass transport) which proceeds fast in comparison with the rates of thermonuclear reactions in the Sun. This enabled us to divide the internal zone (0.6 solar radius) of the Sun on spherical layers (onion like structure) isolated one from another. The set (1) has been solved for each spherical layer with the initial conditions of the standard solar model at the moment when the mixing has been initiated. Of course the results obtained in this way may serve only as guidance. Our aim was to get the averaged values and to see how they differ from the ones given by the standard solar model. Looking for the solutions of this set of equations we were particularly cautious not to go beyond the limits for the parameters of the solar model fixed by helioseismology. This remarkable selectivity of the mixing to the neutrino fluxes (F_{13} is increased while F_{15} from the decay of ^{15}O is almost constant) constitutes the clear signature by which the future experiments may show unambiguously that there is some non stationary process in the Sun and, consequently, in other stars as well, provided that uncertainties of the predicted values are less than the expected changes of the flux. By the present time the main contribution to these uncertainties gives the one for the cross section of the thermonuclear reactions which is around 10% [9]. The parameters used

by the standard solar model (the solar temperature et al) have a lesser impact. It has been shown in [10] that there is a correlation of F_{13} and F_{15} with F_8 so that the ratio of F_{13} (F_{15}) to F_8 has less uncertainty than the fluxes themselves. The total flux of boron neutrinos has been measured precisely in the SNO experiment [11]; this makes possible to reduce the contribution of this uncertainty. Another important issue is the intensity of the mixing, i.e. the exact value of k. In the paper [6] the results were obtained for the case with a certain value of a mass transport coefficient ($k = 10^{-10} yr^{-1}$) and for a certain duration T_{mix} of the mixing on the final stage of the solar evolution. We were tracing how the various parameters of the solar model have been changed with the duration T_{mix} and compared the found changes with the limits established by helioseismology. It was shown that mixing with $k = 10^{-10} yr^{-1}$ and the duration $T_{mix} = 5 \cdot 10^8$ yr is within these limits and this can be used as a partial solution to find the general one. It means that a mass 0.05 of the internal zone of the Sun can be transported to and from the central region of the Sun during the final phase of the solar evolution of the duration $T_{mix} = 5 \cdot 10^8$ yr. This indicates the intensity of the mixing process which does not contradict to present data of helioseismology.

2. Detailed investigation of the case of mixing

Here we investigate this case in more details varying freely k and T_{mix}. On Fig. 1 (a-d) the contours are shown for the standard relative uncertainties 1, 2 and 3 δ (which correspond to the uncertainty 0.5%, 1.0% and 1.5% for the mean molecular weight in the core of the Sun) and for the abundance of hydrogen, helium, carbon and nitrogen on the surface of the Sun. Here δ is a relative uncertainty which corresponds to a standard deviation σ.

One can see from this figure that the most stringent limit comes from the mean molecular weight μ in the core of the Sun and is only mildly affected by the abundance of hydrogen, helium and nitrogen on the surface of the Sun. This result is a good illustration of the power of helioseismology: what concerns the hypothetical scenario the structure of the center of the Sun turns out to be more crucial than what is observed on the surface of the Sun. Figure 2 shows the plots for the increase of the flux of F_{13} (a) and decrease of F_{15} (b) relative to the ones given by a standard solar model.

One can see that substantial increase of F_{13} can be gained by mixing while F_{15} does not experience any noticeable change. The mixing can change also the distribution of ${}^3He$ across the radius of the Sun and, consequently, the flux of ${}^7Be$ neutrinos. The new set of differential equations analogous to (1) can be written to find these changes.

$$\begin{cases} dX(^1H)/dt = -X^2(^1H)\frac{3}{2}(\alpha_{11}+\alpha'_{11}) + X^2(^3He)\frac{1}{9}\alpha_{33} - \\ \qquad -X(^3He)X(^4He)\frac{1}{12}\alpha_{34} + k(X_0(^1H) - X(^1H)) \\ dX(^3He)/dt = -X^2(^3He)\frac{1}{3}\alpha_{33} - X(^3He)X(^4He)\frac{1}{4}\alpha_{34} + \\ \qquad +X^2(^1H)\frac{3}{2}(\alpha_{11}+\alpha'_{11}) + k(X_0(^3He) - X(^3He)) \\ dX(^4He)/dt = X^2(^3He)\frac{2}{9}\alpha_{33} + X(^3He)X(^4He)\frac{1}{3}\alpha_{34} + \\ \qquad +k(X_0(^4He) - X(^4He)) \end{cases} \tag{2}$$

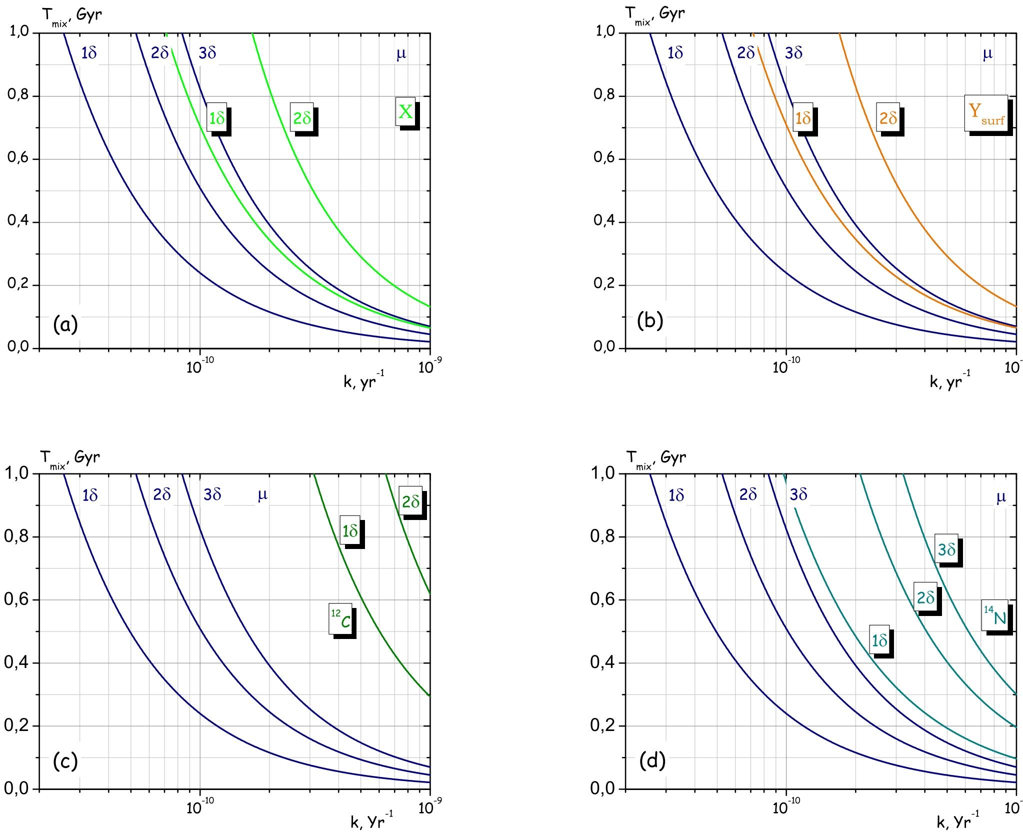

Figure 1. The plots for μ in the core of the Sun and the abundance of ^1H (a), ^4He (b), ^{12}C (c) and ^{14}N (d) on the surface of the Sun.

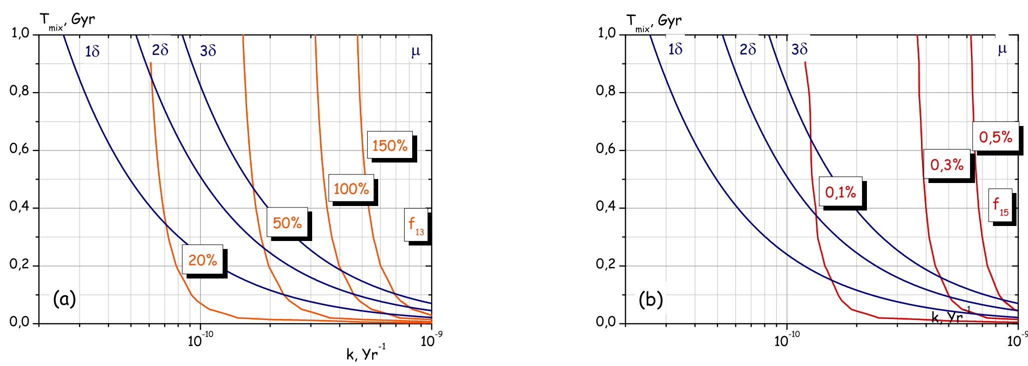

Figure 2. The plots for μ in the core of the Sun and the ones for the increase of F_{13} (a) and decrease of F_{15} (b).

where $\alpha_{ij} = \rho N_A < A_i A_j >$ is the $(A_i + A_j)$ reaction nuclear rate [7, 8]. The flux F_7 of ^7Be neutrinos on the Earth can be written as

$$\Phi_{nu}(^7Be) = \frac{R_\odot^3 \cdot N_A}{3 \cdot 4} \frac{1}{L^2} \int_0^1 r^2 \rho(r) X_{^3He}(r,t) X_{^4He}(r,t) \alpha_{34}(r) dr \qquad (3)$$

where $R_\odot$ – solar radius, L – Sun–Earth distance.

One can see from Fig.3 that the mixing compatible with the results of helioseismology can change the flux of ^7Be-neutrinos by less than 2%.

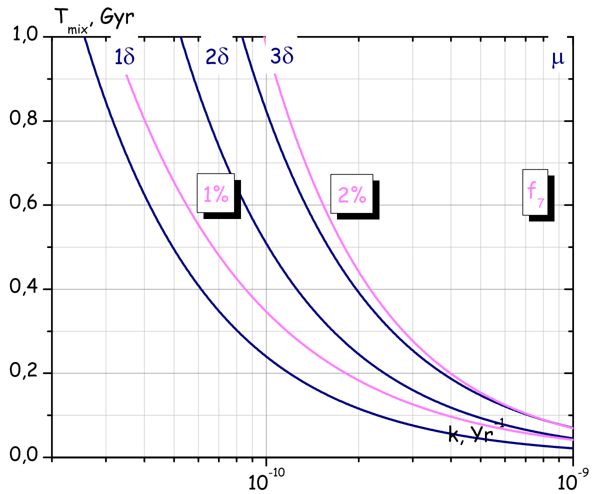

Figure 3. The plots for μ in the core of the Sun and the ones for the increase of F_7.

3. Conclusion

One can see from this analysis that a small freedom is left now by helioseismology for a mixing of a solar matter. For periods comparable with the age of the Sun the mixing can be realized only with $k \leq 10^{-10} yr^{-1}$. For greater values of k the mixing can exist only as the relatively short periods in the Sun's history. However, the remarkable signature of the mixing is the increase of the flux F_{13} while all other neutrino fluxes are practically left unchanged. This conclusion is of general character in a sense that it does not depend upon the specific kind of mixing in coordinates of the internal structure of the Sun. From the experimental point of view it is very interesting to measure precisely the fluxes F_{13} and F_{15}. It has a discovering potential on the non stationary process in the Sun and other stars as well.

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